Pulmonary Function Testing

Introduction

Pulmonary function tests are not difficult to understand. The problem with PFTs is that the words used to describe the different volumes and capacities don't inherently tell you what they measure. They do if you're a pulmonologist or the tech who performs the test every day—but you aren't. So, you will need to do a bit of memorizing. We're going to explain PFTs in a normal patient, a patient with restrictive lung disease, and a patient with obstructive lung disease. The fortunate thing is that most of the values (you don't know what this means yet) go in the same direction. So, after explaining PFTs—what both volumes and capacities are—and after exploring them in restrictive and obstructive lung diseases, we're going to give you the takeaway.

At the end of this lesson, you will need to be able to describe and recognize both obstructive lung disease (OLD) and restrictive lung disease (RLD) as described by the volumes and capacities on PFTs and flow-volume pulmonary function curves. That means OLD volumes, OLD capacities, and OLD curves, _and_ RLD volumes, RLD capacities, and RLD curves. That sounds daunting. We'll make it less so. If you understand OLD and RLD, all you will need to do is ensure you master the names of the volumes and capacities; the rest will fall into place. The shortcut we're taking here is to not teach you any lung patterns other than normal, OLD, and RLD. This stuff can get extremely complicated. We won't let it.

Pulmonary Function Testing: Volumes and Capacities

PFTs are a **noninvasive** diagnostic tool for measuring lung volumes. The patient sits in a glass box that is airtight. The barometric pressure in the box is known, set, and fixed. The patient has their nose plugged so that air can only move through their mouth. They breathe using a mouthpiece connected to a plastic tube that is connected to a machine. Air will come only from the machine into the mouth, and therefore into the lungs. All the air will come from or be blown into the machine. The machine registers volume and pressure, the draws a trace of how much volume is pulled in through the tube or blown out.

The person is asked to breathe normally, called quiet respiration. The machine detects how much air moves in and out during quiet respiration. Then the technician asks the patient to take the biggest breath they can to fill their lungs to the maximum. Do that right now yourself. You've been breathing at quiet respiration reading these notes. Now, take the biggest breath you can (you don't have to plug your nose since there isn't a machine doing any recording). Release it. Back to our patient. The technician instructs the patient to take the biggest breath they can; then, instead of releasing the breath like you just did, the patient is instructed to blow out as hard and fast as they can. You do it now. The biggest breath you can, then blow it out as hard and fast as possible. A lot comes out at the very beginning, but then it sort of peters out. And, since you aren't now dead, the alveoli did not collapse all the way. There is still some air left in you to keep the alveoli open. Follow along with Figure 5.1 as you read the following text.

Quiet respiration gives you the **tidal volume**, the normal breath-to-breath volume. Normal tidal volumes are around 500 mL (it's actually closer to 350 mL, but 500 is a nice round number used whenever exploring this concept, and 500 is what you start your patients on a ventilator on, so learn 500). It is a range. At the end of quiet expiration, you can still blow out more air (that's what you did when you blew out hard). At the end of quiet inspiration, you can still suck more air in (that's what you did when you inhaled as hard as you could). The lung volume in a 70 kg male at the end of inspiration is approximately 3,000 mL, and at the end of expiration is approximately 2,500 mL.

When you take the biggest breath you can, you are filling the lungs to their maximum. Normally, this is approximately 6,000 mL (6 liters). The **inspiratory reserve volume** is how much air a person can inhale

above the peak of tidal volume, above the volume of air in the person at the end of inspiration. Tidal volume peaks at 3,000 mL. The maximum a person can get to is approximately 6,000 mL, so a normal inspiratory volume is 3,000 mL.

When you force it all out, you are removing as much air as possible. But not all the air in the lungs leaves—some remains behind to keep the alveoli open. No matter how hard anyone tries, they will not be able to exhale all the air in their lungs. The only way that happens is if the lungs are removed from the thorax and placed on a table—in the absence of the elastic recoil of the chest wall, the elastic recoil of the lungs takes the alveoli to a lung volume of zero. The amount of air that you **cannot breathe out** is called the **residual volume**. The amount of air you <u>can</u> breathe out below the tidal volume is the **expiratory reserve volume**. The lowest that tidal volume gets is approximately 2,500 mL. The amount you cannot blow out is approximately 1,000 mL. Normal expiratory reserve volume is, therefore, approximately 2,000 mL.

Tidal volume is, in normal, quiet inspiration, a range from the peak volume inhalation and the valley volume exhalation. The **reserve volumes** are how much air the person can breathe in (inspiratory) above tidal volume and can breathe out (expiratory) below tidal volume. The **residual volume** is how much air is left over after the expiratory reserve volume has been exhaled.

Take a look at the left half of Figure 5.1. Do the exercise of quiet respiration, deep inhale, forceful exhale. Trace the lines in the figure with their correlates. Then come back here to talk about capacities.
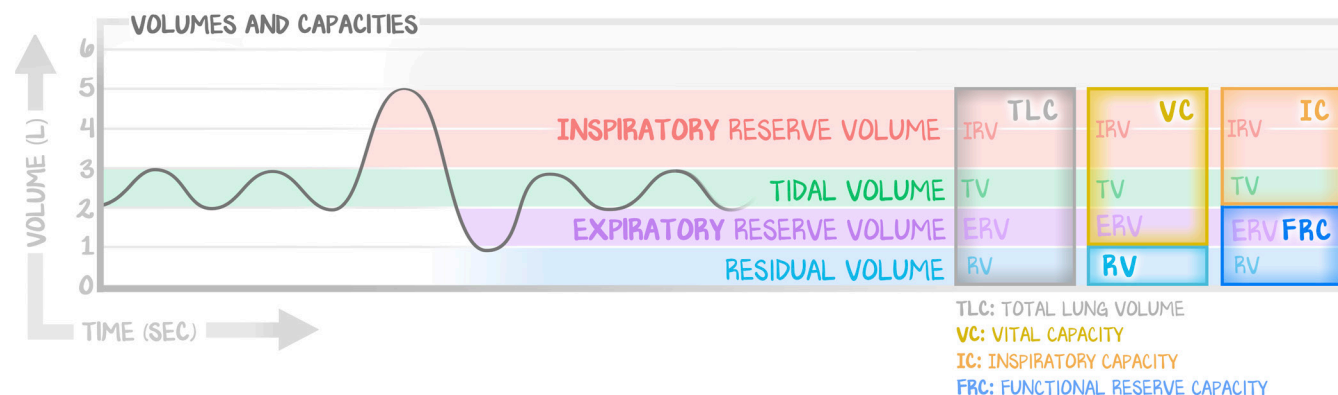
Figure 5.1: Lung Volumes and Capacities
A visual representation of the lung volumes as a person goes through pulmonary function testing. The volumes can be combined, creating capacities. Capacities are just the sum of lung volumes, and those lung volumes must be continuous with one another. The sine-wave shape is generated by the gradual increase in volume over time during inhalation and the gradual decrease in volume over time during exhalation. Each peak of the curve is the end of inhalation. Each valley of the curve is the end of exhalation.

The idea of volumes is challenging for the human brain. We naturally think, *"how much can we breathe in vs. how much can we breathe out."* That isn't what the inspiratory or expiratory reserve volumes are. Those volumes are artificial constructs of the waveform trace. That's why Figure 5.1 is color-coded the way it is. Blow all the air out that you can, then take the biggest inhalation possible. What you just did was go to the bottom of the expiratory reserve volume on exhalation, then inhaled up to the top of inspiratory reserve volume. That's "how much air you can breathe in . . . from the lowest volume your lungs can get." What you breathed in there is called the **vital capacity**. The name doesn't make any sense, so use whatever memory tactic you want to remember this. The vital capacity is the summation of all volumes except the residual volume. Go back to Figure 5.1, look at the right side; make sure you understand what vital capacity is.

Since the waveform is continuous, and the machine tells us what the peak and valley of the tidal volume are, we can start combining the different color-coded volumes. The vital capacity was the inspiratory volume, the tidal volume, and the expiratory volume. Well, let's start adding other colors together. If you take the lowest value of the tidal volume (quiet expiration) and add it to the inspiratory reserve volume (the maximum amount that can be breathed in), you get the **inspiratory capacity**. The **functional residual capacity** is what's left over, the combination of the expiratory reserve volume and the residual volume.

The last one is easy. The **total lung capacity** is the sum of all the volumes together. There isn't an inverse of the vital capacity. There isn't one because it doesn't do anything for us clinically. There is no summation of the tidal volume, expiratory reserve volume, and residual volume.

Flow-Volume Loops

THE BIGGEST X-AXIS NUMBER IS CLOSEST TO THE Y-AXIS. Why. Would anyone. Intentionally do this? We don't know. But that is the way it is. There is probably a really good reason. But it is something you must accept as true. Another trace is generated by the person breathing in the plastic tube. It is interrelated with the previous volumes and capacities, so we'll use what you already know from above to explain what's going on in the flow-volume loops. BUT: the thing you really need to know how to do is see a flow-volume loop and recognize it as normal, obstructive (weird slope, shift to left), or restrictive (normal, but smaller and shifted to the right). But before we get to the shortcuts, let's make sure you grasp the technique. Use Figure 5.2 as a reference.
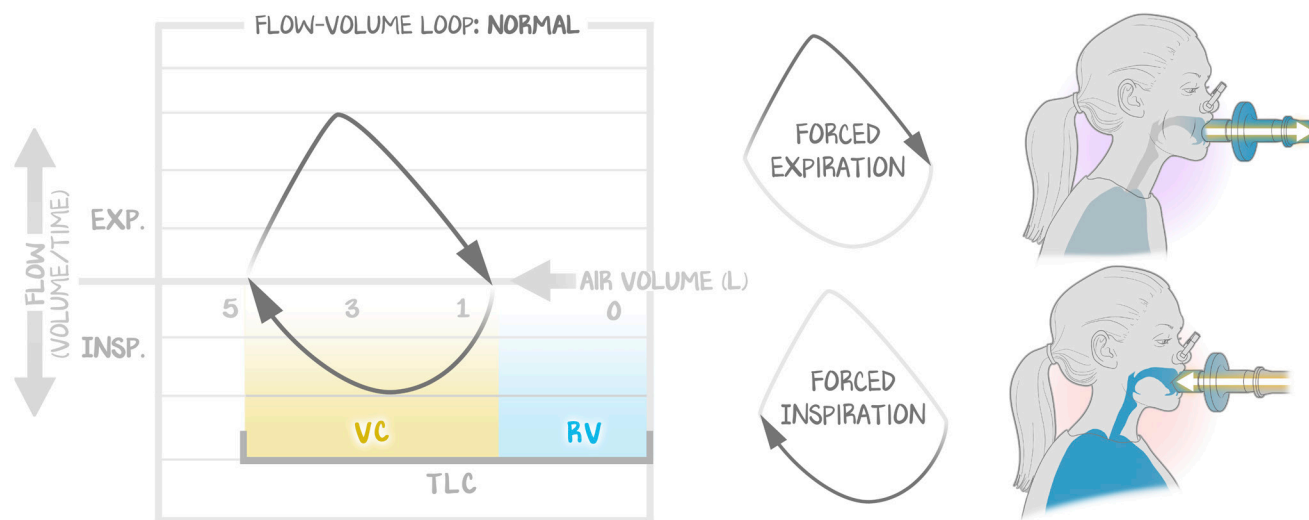
Figure 5.2: Understanding Normal Flow-Volume Loops
Starting at the forced expiratory volume, active inspiration brings air in, moving left. Flow is moving out of the machine and into the patient. "Out of the machine" means "gets negative," or down. Down and left is breathing in. Once the maximum inhalation is achieved, forced expiration begins. Lots of air leaves the patient and goes into the machine, reading it as positive, or above the x-axis. A lot of air comes out very quickly, and then the flow tapers off as the patient reaches the bottom of the forced expiratory volume.

The x-axis is volume. As someone inhales, their lung volume goes up. When lung volumes go up, the trace moves to the left. As someone exhales, their lung volume goes down. When lung volumes go down, the trace moves to the right.

The y-axis is the flow rate. A rate is a volume per time. The y-axis is not time. A person might inhale over 10 seconds or 1 second. If they inhale slowly, the flow will be small, and the y-axis shallow. If they inhale quickly, the flow will be fast, and the y-axis peaked. Below the x-axis, air is flowing out of the machine and into the person. Flowing out of the machine is a negative number. Above the x-axis, air is flowing out of the person and into the machine. Flowing into the machine is registered as a positive number. The technician instructs the patient to blow out forcefully, as much as they can as fast as they can.

Flow-volume loops trace how much air there is in the person against how fast the air moves into or out of the person. They also allow the visualization of residual volume (from the end of expiration to 0 on the x-axis), the vital capacity (the x-axis between the intercepts of the loop), and therefore the combination of those two values, the total lung capacity. They do not demonstrate any other volumes or capacities.

There are a lot of flow-volume loops you could look at. Flow-volume loops go beyond just diagnosing normal, restrictive, and obstructive lung disease. Do not go into that level of detail until your pulmonary fellowship.
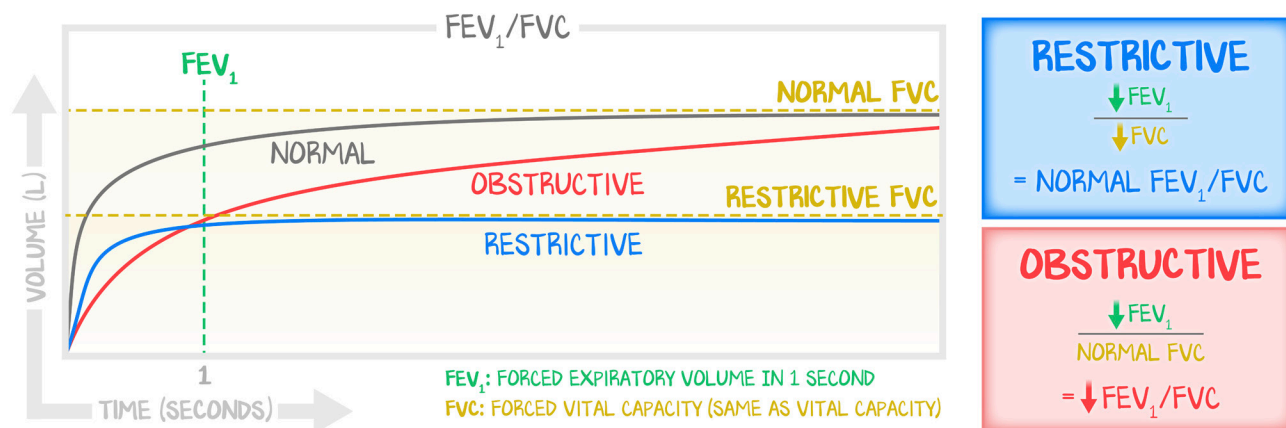
FEV1/FVC Ratio

Flow-volume loops visualize the FEV1/FVC well, but only if you know what you're looking at. The FVC is the forced vital capacity, aka the vital capacity. Yes. The vital capacity and the forced vital capacity are the same thing, yet there are two names. We didn't make this stuff up, and this is the way it is. The FVC is the full volume of inspiration and expiration, everything not the residual volume. The vital capacity, the FVC, is the distance on the x-axis between inspiration and expiration. Take a look at Figure 5.3 and make sure you get the visual—within the flow-volume loop on the x-axis is the FVC, to the right of the flow-volume loop is the residual volume.

Time is implied in a flow-volume loop but not plotted. As we follow the trace above the x-axis, the leftmost part is the start of expiration. The rightmost part is the end of expiration and the start of inspiration. What is plotted on the y-axis is the flow rate, how fast air is moving, how much air per unit of time. The high peak at the beginning of expiration (it is highest on the left) means that **more air is leaving** at the beginning of expiration than at the end. Take the biggest breath you can, then blow it all out hard. Could you sense that more air came out in the beginning, and you had to strain your abdominals to get the last bit out? That peak is measuring how much comes out in the **first second**. This is called the **FEV1** (forced expiratory volume in one second).

The FEV1/FVC ratio is useful for diagnosing obstructive lung disease. The shape of the flow-volume loop can show you this information, but it's best shown on a different graph that you won't see on pulmonary function tests. The FEV1/FVC is reported as a percentage. Under 70% is obstructive lung disease. Over 70% anything else other than obstructive lung disease. Memorizing that fact negates the necessity for this section. But on a licensing exam, you may not be given the percentage and may be asked to infer that information from the flow-volume loop alone.

Figure 5.3 shows a plotting with time on the x-axis and volume on the y-axis. The FEV1 is how much air comes out in one second. The FVC is the maximum that can come out. In a normal patient, 70% or more of the total air that will come out comes out in one second. In restrictive lung disease, the total air that will come out is lower than the amount that will come out in a normal person. But, the ratio of how much comes out in one second to the total amount that will come out is proportional to normal—70% or more of the total air that will come out comes out in one second. In obstructive lung disease, because resistance takes time to overcome, the total amount of air to come out will be about the same as normal, but it has to come out gradually. So, the ratio of how much comes out in one second to the total amount will be greatly reduced.

Figure 5.3: FEV1/FVC
PFTs are not plotted like this. But this graph is used to demonstrate to a new learner that it is the FEV1/FVC ratio, not the FEV1 or FVC alone, that makes the diagnosis. The FEV1 is lower than normal in both obstructive and restrictive lung disease. But the restrictive curve is the same shape as the normal curve, and RLD's FEV1/FVC is also normal. On the other hand, the obstructive curve approaches the normal FVC, but at a much slower rate. The FEV1/FVC is decreased in obstructive lung disease.

Similar to the discussion in Figure 5.3, Figure 5.4 gets us thinking about the shape of the flow-volume loops in regard to obstructive vs. restrictive lung disease. You are supposed to get an FEV1/FVC reported as a percentage. But if you aren't given that, you can see that normal flow-volume loops and restrictive lung disease flow-volume loops have the same shape; restrictive lung disease is just not as tall and is shifted to the right. Obstructive lung disease, however, is shifted to the left, wider, and has that weird slope that's different than in the other two. That weird slope is the reduced FEV1/FVC.
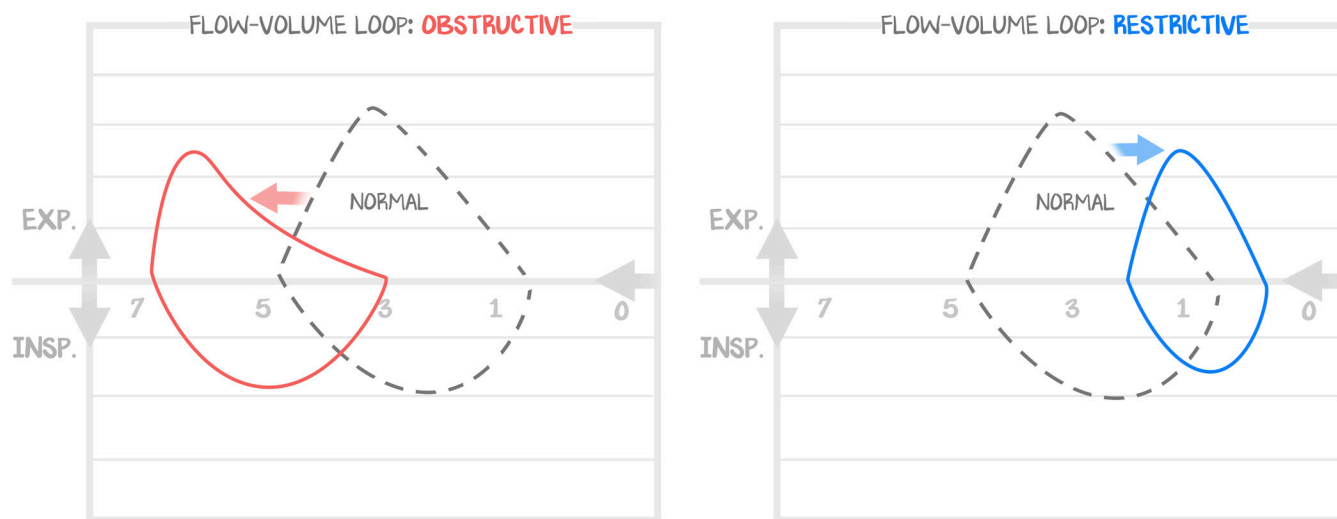
Figure 5.4: Flow-Volume Loops' Shapes Communicate Disease
Obstructive lung disease not only shows higher volumes, but the shape of the expiration curve is overtly different than the other curves, giving it away as obstructive lung disease. The normal curve and the restrictive curve have the same shape, except the restrictive lung has lower values, so it is smaller and shifted to the right. : Alternatively, you can use a pulmonologist teaching tool—ignore the inspiratory curve (everything below the line), and you will reveal a *"ski slope for obstructive,"* and *"wizard hat for restrictive."* Give it a try.

Diffusion of Carbon Monoxide (DLCO)

Carbon dioxide (CO_2) always equilibrates, regardless of how bad the diffusion barrier is affected. Oxygen does not. Oxygen is a diffusion-limited gas in any pathologic state. Carbon monoxide is a diffusion-limited gas. The DLCO assesses whether there is a diffusion barrier problem. The patient inhales a known amount of carbon monoxide. The patient then exhales into a machine that reads how much carbon monoxide is present. By knowing how much went in (the predetermined amount) and how much came back out (the measured amount), the machine can calculate how much diffused into the capillaries (a calculated amount). A reduced DLCO is indicative of an impaired diffusion barrier. That could be the emphysema-induced loss of surface area, or it could be fibrosis, decreasing diffusion by increasing the diffusion barrier thickness. If a patient had CHF and were volume overloaded, where there was edema between the alveoli and the capillary, the DLCO would also be reduced. But we don't do pulmonary function testing on patients with CHF and volume overload. We would diurese them first, get them dry, and then do the PFTs.

The DLCO likely confirms the information you already know. The only way a patient can be hypoxemic and have a normal DLCO is if they are living at a high altitude (which you would know), or not breathing deeply enough (obesity hypoventilation syndrome and neuromuscular weakness). These are things you could deduce from the patient history. However, a licensing exam may withhold information in order to assess your understanding of the DLCO portion of the PFTs.

Obstructive Lung Disease

In obstructive lung disease, there is trouble getting air **out of the lungs**. No trouble getting air into the lungs, just getting air out. We'll explain why in the next lesson. Just accept this as truth for now. There is trouble getting air out of the lungs because of increased resistance in the airway. Resistance takes time to overcome. In OLD, the **FEV1/FVC is less than 70%**—the amount a person with OLD can exhale in one second is lower than the amount a healthy patient can exhale because the resistance takes time to overcome.

Because patients with OLD have trouble getting air out of the lungs, the **volumes will be higher**. A higher lung volume means that at the end of inspiration and expiration, the amount of volume in the lung will be higher than normal. "Higher than normal" means a **left shift** on the flow-volume curves. The lung volumes are up because they can't get air out. That means the **residual volume is higher**. The residual volume contributes to the functional residual capacity and the total lung capacity, which also increase. **What doesn't change is the vital capacity**—tidal volume, inspiratory reserve volume, and expiratory reserve volume don't change. OLD is, therefore, characterized by an **increased residual volume**. Any volumes or capacities that are calculated using the residual volume would, therefore, also be increased—**functional residual capacity** and **total lung capacity**. Since the vital capacity is the same, the width of the flow-volume loop is the same. Because resistance takes time to overcome, the height of the flow-volume curve will be stunted.

Look at Figure 5.5 and make sure you understand the shape of the curve, the size of the boxes, and why it's different than normal.
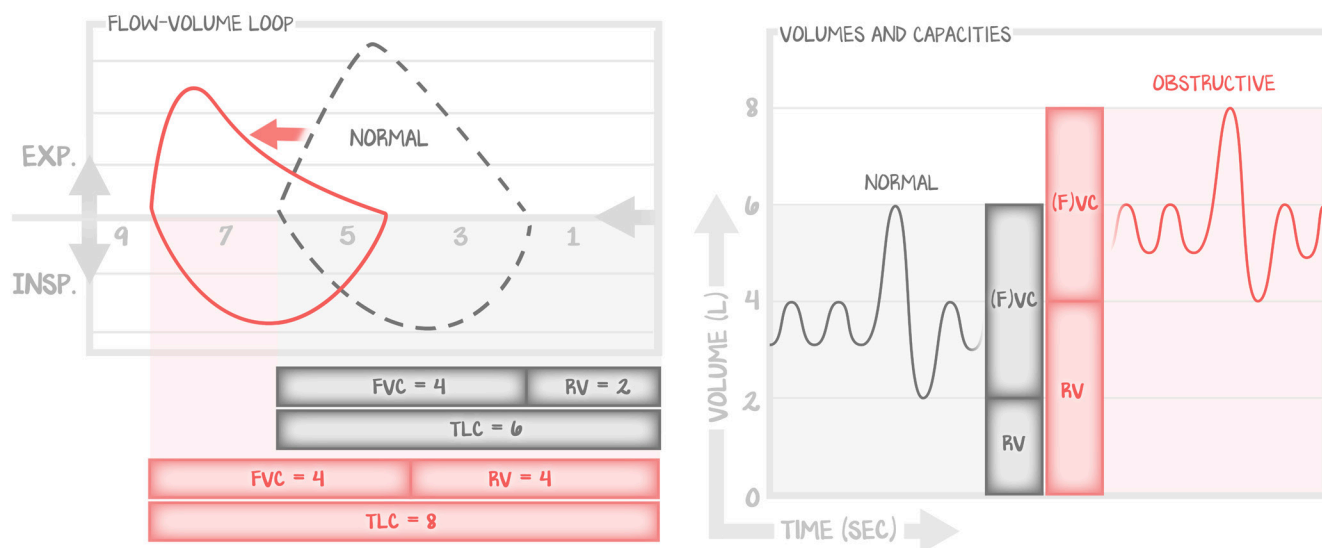
Figure 5.5: Obstructive Lung Disease Volumes, Capacities, and Flow-Volume Loops
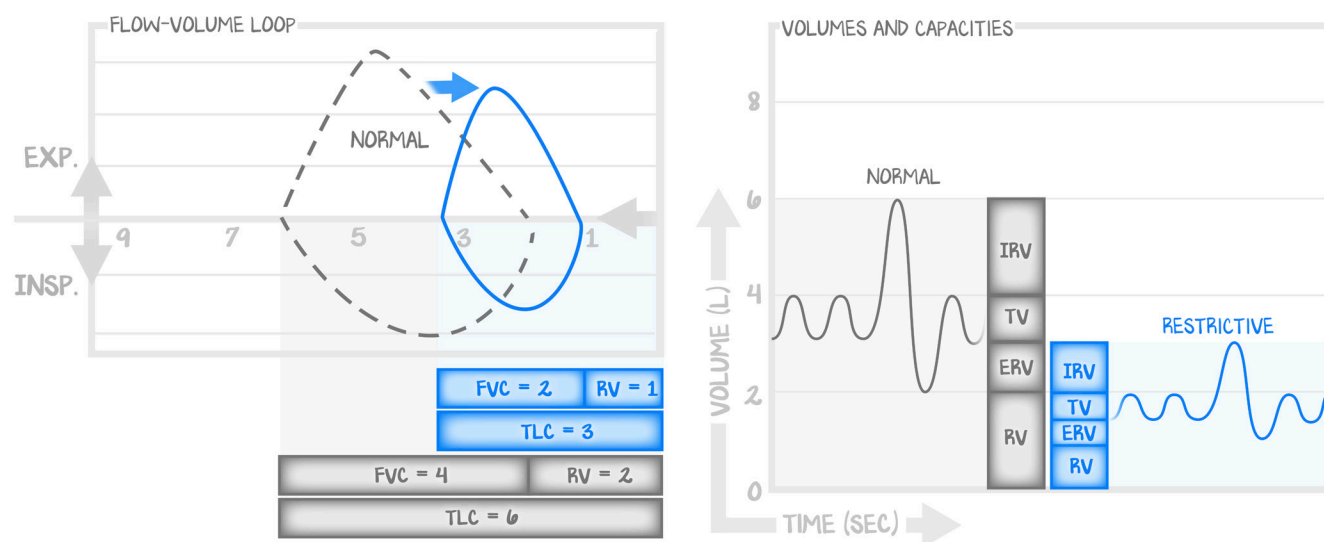In obstructive lung disease, the flow-volume loop is shifted to the left; the vital capacity is unchanged, as evidenced by the same distance on the x-axis. The total lung capacity is higher, as evidenced by the peak of 8 L. The slope of the FEV1 is notched. This can be visually represented as on the right, showing equal FRC, just at higher lung volumes—higher RV and TLC. This is, again, a shift to the left.

Restrictive Lung Disease

In **restrictive lung disease,** there is trouble getting air **into the lungs**. Whatever gets in has no trouble getting out. That inherently means there will be smaller volumes. Less air into the lungs means there is less to blow out. Having less air in them means there is a **reduced residual volume**. Because residual volume contributes to expiratory reserve volume and total lung capacity, **expiratory reserve volume and total lung capacity are decreased**. This is the same logic we used in obstructive lung disease. The physiology is reduced lung volume. The math correlates to the capacities.

In restrictive lung disease, **vital capacity is also reduced**. Since the vital capacity is reduced, the flow-volume curve is **shifted to the right**. Because there isn't as much air to move, the flow rates are also decreased. The **FEV1** is reduced, and the **FVC** (vital capacity) is reduced. But the FEV1 is reduced *because* the FVC is reduced. The **FEV1/FVC** is normal. Shifted to the right, stunted height, but the **same shape** as normal expiration.

Restrictive lung disease can be caused either by fibrosis or by mechanical failure (more on that in Pulmonary: Lung #8: *Restrictive Lung Disease*). In mechanical failure, the alveoli are normal, and the diffusion barrier unimpaired. For RLD caused by **fibrosis, the DLCO will be decreased**.

Figure 5.6: Restrictive Lung Disease Volumes, Capacities, and Flow-Volume Loops
The shape of the flow-volume loop of restrictive lung disease is the same as normal, but smaller, shifted to the right, and not as tall. The vital capacity falls with a falling tidal volume, IRC, and ERC. The residual volume is smaller, as evidenced by its being closer to zero on the axis. This can be visualized as on the right, with all the volumes scrunched down.